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Citation: Appl. Phys. Lett. 109, 202404 (2016); doi: 10.1063/1.4967843
View online: http://dx.doi.org/10.1063/1.4967843
View Table of Contents: http://aip.scitation.org/toc/apl/109/20
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Spin transfer torque devices utilizing the giant spin Hall effect of tungsten
Spin-torque ferromagnetic resonance measurements utilizing spin Hall magnetoresistance in W/Co$_{40}$Fe$_{40}$B$_{20}$/MgO structures

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(Received 16 September 2016; accepted 3 November 2016; published online 15 November 2016)

We study the magnetic properties of W/Co$_{40}$Fe$_{40}$B$_{20}$ (CoFeB)/MgO films using the spin-torque ferromagnetic resonance (ST-FMR) technique. This study takes the advantage of the spin Hall magnetoresistance (SMR) for generating an oscillating resistance, which is one of the necessary requirements for obtaining mixing voltage in the ST-FMR technique. We have measured both the as-grown and the annealed samples with different CoFeB layer thicknesses, which include the in-plane and out-of-plane magnetic anisotropies. The spectra for these two types of anisotropies show distinct signatures. By analyzing the ST-FMR spectra, we extract the effective anisotropy field for both types of samples. In addition, we investigate the influence of CoFeB thickness and annealing on the Gilbert damping constant. Our experiments show that by taking advantage of SMR, the ST-FMR measurement acts as an effective tool with high sensitivity for studying the magnetic properties of ultrathin magnetic films.

Published by AIP Publishing. [http://dx.doi.org/10.1063/1.4967843]

Spin-torque ferromagnetic resonance (ST-FMR) is emerging as an effective technique for studying the properties of magnetic materials since it was reported by Tulapurkar and Sankey et al.$^{1,2}$ In the first stage of this method, a radio frequency current ($I_{rf}$) is applied to exert an oscillating torque on the magnetic moment and to make it oscillate around the equilibrium state, often due to the spin-transfer torque. This results in the resistance oscillation ($R_{df}$) due to the magnetoresistance effects, such as tunnel magnetoresistance (TMR) and giant magnetoresistance (GMR).$^{1-3}$ Consequently, a rectified dc voltage is generated as a result of the mixing of the $I_{rf}$ and the $R_{df}$. Hence, the ST-FMR spectrum provides rich information about material properties, such as resonance frequency and field, magnetic anisotropy and Gilbert damping constant ($\alpha$).$^{2,5}$

Alternatively, spin-orbit torque (SOT)$^{6-8}$ has also been employed for exciting magnetization oscillations in the ST-FMR technique, where $I_{rf}$ is applied in the film plane, and $R_{df}$ usually originates from the anisotropic magnetoresistance (AMR) effect.$^{7-13}$ In this scheme, unlike TMR or GMR cases,$^{1-3}$ a reference magnetic layer is not required, which simplifies the device structure. However, AMR usually decreases with a decrease in the thickness of film,$^{14}$ which dramatically limits the studies of ultrathin ferromagnetic materials using ST-FMR.

More recently, spin Hall magnetoresistance (SMR) was observed in the heavy metal (HM)/ferromagnetic insulator (FI) or HM/ferromagnetic metal (FM) structures, which depends on the angle between the magnetization ($\bm{M}$) and the direction of the spin-polarized electrons induced by the spin Hall effect.$^{15}$ The ST-FMR utilizing SMR has been used to study magnetic properties in the HM/FI structure.$^{16-18}$ For HM/FM structure, compared with AMR, SMR is more dependent on the spin-dependent scattering at the HM/FM interface, which therefore makes it less dependent on the FM thickness. Experimentally, large SMR has been observed in the W/CoFeB/MgO structures with the CoFeB layer as thin as 0.8 nm.$^{19,20}$ The sizable SMR enables studying the magnetic properties of ultrathin CoFeB ferromagnetic layers, utilizing the ST-FMR technique.

In this work, we investigate the magnetic properties of both the as-grown and the annealed W/Co$_{40}$Fe$_{40}$B$_{20}$(CoFeB)/MgO multilayers with different CoFeB layer thicknesses using the ST-FMR technique. We obtain pronounced ST-FMR spectra due to the large SMR in the W/CoFeB bilayers in all the samples. By analyzing the ST-FMR spectra, we can study the influence of annealing and CoFeB layer thickness on the anisotropy and damping constants. This work demonstrates that the SMR-based ST-FMR is an effective method to probe the magnetic properties of ultrathin ferromagnetic films.

The film structures studied in this work consist of W(5)/CoFeB(r)/MgO(2)/Ta(2) (thicknesses in nm), which were deposited on thermally oxidized Si (001) substrates using a high-vacuum magnetron sputtering system at room temperature. The Ar sputtering pressure was 3 mTorr with a base pressure of less than $2 \times 10^{-8}$ Torr. Subsequently, the multilayer films were patterned into standard Hall bars (length of 130 $\mu$m and width of 20 $\mu$m) and rectangular-shaped strips (length of 20 $\mu$m and width of 20 $\mu$m) using optical lithography and dry etching for SMR and ST-FMR measurements, respectively. Cr(10)/Au(100) metal stacks were deposited as contacts for electrical measurements.

The saturation magnetization ($M_s$) and the effective magnetic anisotropy energy ($K_{eff}$) of the as-grown samples were first characterized using vibrating sample magnetometer (VSM), as the reference for the ST-FMR measurement. All as-grown films exhibited in-plane magnetic anisotropy. Fig. 1(a) shows the nominal CoFeB thickness dependence

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Fig. 1(b). By fitting the data with the following equation:

\[ M_{s} = \frac{1008 \pm 50 \text{ emu/cm}^{3}}{1 - \frac{t_{\text{CoFeB}}}{0.32 \pm 0.10 \text{ nm}}} \]


The value of \( K_{e} \) is determined to be about 0.70 \( \pm 0.02 \) \( \text{erg/cm}^{2} \). The negative values of \( K_{e} \) indicate the in-plane anisotropy nature of all of these as-grown films.

Figure 2(a) shows the variation of the longitudinal resistance \( R_{yy} \) as the magnetic field (with the magnitude of 2T) rotating in three planes (the \( xy \)-, \( xz \)-, and \( yz \)-planes). Since the magnetic field is larger than the saturation fields of all the samples, the magnetization aligns along the magnetic field direction. The \( R_{yy} \) varies while the magnetization rotates in the \( xy \)- and \( xz \)-planes, but remains nearly constant while the magnetization rotates in the \( yz \)-plane, which are the typical signatures of SMR.\(^{19,20} \) When a current is applied along the \( y \)-direction, as marked in Fig. 2(b), it generates accumulated spin polarized electrons at the HM/FM interfaces due to the spin Hall effect.\(^{15} \) The direction of spin polarization is along the \( x \)-direction. The \( R_{yy} \) depends on the relative angle of \( M \) with respect to the \( x \)-direction. Fig. 2(c) shows the dependence of SMR on the CoFeB layer thickness. The SMR slightly increases and reaches the saturated value (about 0.5%) when the CoFeB layer thickness is greater than 1.0 nm. The SMR does not significantly rely on the CoFeB layer thickness, which is consistent with the previous work.\(^{20} \) The saturated value of SMR in our device is comparable to that reported in Ref. 19, but slightly smaller than that reported in Ref. 20. The difference in SMR value may be due to the difference in the phase of the W layers. In this structure, the AMR is negligible since the resistance is almost invariable when the field rotates in the \( yz \)-plane.

The schematic diagram of the ST-FMR measurement setup is shown in Fig. 3(a). A microwave-frequency (GHz) charge current \( I_{\text{cof}} \) with a power of 4 dBm and modulated \( f_{\text{mod}} \approx 20 \text{ kHz} \) by the lock-in amplifier was applied to the device. The rectified voltage was detected by a lock-in amplifier. An in-plane magnetic field with a fixed angle \( \theta_{H} \) of 45° was swept between \(-0.5 \text{ T} \) and \(+0.5 \text{ T} \). Fig. 3(b) shows the ST-FMR spectra for the as-grown sample with a 1.1 nm thick CoFeB layer. The results can be well fitted to a Lorentzian function consisting of a symmetric and an anti-symmetric Lorentzian component:

\[ V_{\text{mix}} = \frac{\Delta^{2}}{\Delta^{2} + (H_{\text{ext}} - H_{0})^{2}} + A \frac{\Delta(H_{\text{ext}} - H_{0})}{\Delta^{2} + (H_{\text{ext}} - H_{0})^{2}}. \]

where \( \Delta \) is the linewidth (full width at half maximum), \( H_{0} \) is the resonant magnetic field, \( S \) is the symmetric Lorentzian coefficient that is proportional to the oscillating spin current \( I_{s,\text{sf}} \), whereas \( A \) is the antisymmetric Lorentzian coefficient.

**FIG. 2.** (a) Longitudinal resistance \( R_{yy} \) as a function of the angle of magnetization for a 1.2 nm as-grown CoFeB film. The magnetization rotates in the \( xy \) (\( \theta = 90^\circ \)), \( xz \) (\( \phi = 0^\circ \)), and \( yz \) (\( \phi = 90^\circ \)) planes. (b) The schematic diagram of the coordinates and measurement. The magnetization is rotated by rotating an external magnetic field of 2T, which is larger than the saturation fields for all the different thickness samples. (c) The CoFeB thickness dependence of the spin Hall magnetoresistance.
that is proportional to the Oersted field \( (H_0) \) generated by \( I_{c,rf} \). The inset shows the spectrum of 6 GHz for both positive and negative magnetic fields. Fig. 3(c) shows the resonance frequency \( f \) as a function of the resonant field \( H_0 \) for different CoFeB layer thicknesses. The results are fitted using the Kittel equation \( f = \gamma / (2\pi) \sqrt{\mu_0 H_0 (\mu_0 H_0 + 4\pi M_{\text{eff}})} \), \( (3) \)

where \( \gamma \) is the gyromagnetic ratio. The extracted effective magnetization fields \( (4\pi M_{\text{eff}}) \) are shown in Fig. 3(d). \( 4\pi M_{\text{eff}} \) decreases dramatically from 1.28 ± 0.006 T to 0.010 ± 0.003 T as the thickness of CoFeB layer reduces from 3 nm to 0.8 nm. The decreasing \( 4\pi M_{\text{eff}} \) reflects the gradual increasing contribution of the interfacial anisotropy with decreasing thickness, as expected from \( (23) \) the equation \( 4\pi M_{\text{eff}} = 4\pi M_s - 2K_i/M_s t_{\text{CoFeB}} \). The effective magnetic anisotropy \( K_{\text{eff}} \) was calculated using \( K_{\text{eff}} = -\frac{1}{2} M_s 4\pi M_{\text{eff}} \). \( K_{\text{eff}} \) as a function of the thickness of CoFeB layer was determined by the ST-FMR, as shown in Fig. 1(b), which is consistent with the results obtained using VSM.

We have also studied the magnetic damping based on the frequency dependence of resonance linewidth as shown in Fig. 4(a). The resonance linewidth, which usually includes intrinsic and extrinsic origins, is given by \( (9,11) \)

\[
\Delta = \Delta_0 + (2\pi x/\gamma f).
\]  

\( \Delta_0 \) is the extrinsic contribution (e.g., inhomogeneous broadening) to the linewidth, which is usually independent of frequency. The second term is the intrinsic contribution, which is linearly proportional to the frequency. The values for studied samples were obtained by fitting the data, as shown in Fig. 4(b). The \( \alpha \) value increases from 0.0097 ± 0.0001 to 0.0400 ± 0.0005 when the CoFeB thickness decreases from 3.0 nm to 1.0 nm. Such a thickness dependence of \( \alpha \) is attributed to two-magnon scattering \( (24,25) \) and the spin pumping effect. \( (25-27) \) The \( \alpha \) values in our structures are comparable to the results in the W/CoFeB bilayer structure reported by Pai et al. \( (9) \) but a little larger than that of Ta/CoFeB/MgO \( (28) \) which is likely due to the different interfacial morphologies and spin mixing conductance in spin pumping. \( (25,27) \) The inset of Fig. 4(a) shows the results for the sample with the 0.8 nm CoFeB layer, which cannot be fitted linearly. This nonlinearity probably originates from the fact that the 0.8 nm thick CoFeB film becomes discontinuous, and the magnetization is not saturated in the film plane, i.e., there exists a distribution of magnetization angles in the film relative to the applied field direction. \( (29) \)

FIG. 3. (a) The schematic diagram of the setup for ST-FMR measurements. The \( I_{c,rf} \) indicates the charge current (orange arrow), and the \( I_{s,rf} \) indicates the spin current (yellow arrow). \( H_{\text{ext}} \) is the applied external magnetic field. \( \theta_{\text{H}} \) is the angle between \( H_{\text{ext}} \) and the device channel. (b) The ST-FMR spectra for the sample with \( t_{\text{CoFeB}} = 1.1 \) nm. The solid curves are the fits to a sum of symmetric and antisymmetric Lorentzian functions. The inset shows the spectrum of 6 GHz for both positive and negative magnetic fields. (c) Resonance frequency \( f \) as a function of the resonant field \( H_0 \) for W(5)/CoFeB(t)/MgO devices with thicknesses of 0.8, 1.0, 1.1, 1.2, 1.5, 2.0, and 3.0 nm. The solid curves are fittings of the Kittel formula. (d) The effective magnetization fields, \( 4\pi M_{\text{eff}} \) for W(5)/CoFeB(t)/MgO were determined by the Kittel equation fitting as a function of CoFeB thickness.

FIG. 4. (a) The linewidth \( \Delta \) extracted from the fitting of ST-FMR signal versus the resonance frequency \( f \) for different CoFeB thicknesses. The solid lines are the linear fittings. The inset is the linewidth \( \Delta \) versus resonance frequency \( f \) for the sample with the 0.8 nm CoFeB layer, which cannot be linearly fitted. (b) The Gilbert damping constant \( \alpha \) as a function of CoFeB thickness.
We next show the results for the samples annealed at 250 °C for 0.5 h in a vacuum environment. After annealing, the samples with $t_{\text{CoFeB}} \geq 1.2$ nm show an in-plane magnetic anisotropy, and the samples with $t_{\text{CoFeB}} = 1.0$ and 1.1 nm show a perpendicular magnetic anisotropy, determined by the anomalous Hall measurement (not shown here). For the samples with in-plane magnetic anisotropy, the ST-FMR spectra are similar to those of the as-grown samples. However, the spectra of the perpendicularly magnetized samples are significantly different from those of the in-plane samples. In the spectra of the perpendicularly magnetized samples, additional peaks are observed as shown in Fig. 5(a). Therefore, the resonance frequency dependence on the resonant field exhibits an anomalous Hall measurement (not shown here). For the samples with in-plane magnetic anisotropy, the ST-FMR spectra show a perpendicular magnetic anisotropy, determined by the Kittel equation. The emergence of this additional branch is because the magnetization is not aligned with the external magnetic field in the perpendicularly magnetized samples is because the magnetization is not aligned with the external magnetic field as the magnitudes of the fields are below the alignment field ($H^\text{HFMR}$). We analyze the experimental results using the previously derived FMR condition

$$\left(\frac{2nf}{\gamma}\right)^2 = W_x W_y,$$  \hspace{1cm} (5)

where $W_x$ and $W_y$ are the stiffness fields for the system with the first and second orders of PMA, respectively, that are defined as

$$W_x = \mu_0 H \cos\left(\frac{\pi}{4} - \theta\right) - \mu_0 H_1 \sin^2\left(\frac{\pi}{4} - \theta\right)$$

and

$$W_y = \mu_0 H \cos\left(\frac{\pi}{4} - \theta\right) + \mu_0 H_1 \cos^2\left(\frac{\pi}{4} - \theta\right)$$

$$+ \mu_0 H_2 \left(3 \sin^2\left(\frac{\pi}{4} - \theta\right) \cos^2\left(\frac{\pi}{4} - \theta\right) - \sin^4\left(\frac{\pi}{4} - \theta\right)\right),$$

(6)

where $H$, $H_1$, and $H_2$ are the external magnetic field, the first order and second order anisotropy fields, respectively, $\theta$ is the polar angles of the magnetization $\mathbf{M}$ with respect to the $z$-axis. The magnetic free energy density for the system can be described as

$$F = -\mu_0 \mathbf{H} \cdot \mathbf{M} + \mu_0 H_1 \cos^2\theta - \mu_0 H_2 M_{\text{eff}} \cos^4\theta - \mu_0 H_3 M_x M_y,$$  \hspace{1cm} (7)

The first term is the Zeeman energy, and the last two terms are the first and second order PMA terms. The equilibrium value of $\theta$ could be calculated by minimizing the free energy. By using Equations (5)–(7) to fit the frequency dependencies of the resonant fields for the samples with 1.1 nm and 1.0 nm CoFeB layer, as displayed in Fig. 5(b), $\mu_0 H_1$ values are determined to be $-199.80 \pm 0.07$ mT and $-166.88 \pm 0.02$ mT, and $\mu_0 H_2$ values are found to be 0.98 ± 0.01 mT, and 1.26 ± 0.01 mT. The effective magnetization fields can be further calculated to be $4\pi M_{\text{eff}} = \mu_0 H_1 + \frac{1}{2} \mu_0 H_2$, as shown in Fig. 5(c). Here, the alignment field, $H^\text{HFMR}$, is approximately equal to the absolute value of $H_1$. For $H > H^\text{HFMR}$, $\mathbf{M}$ is tilted to in-plane by the external field, and the ST-FMR signal, in this case, is similar to that of the sample with in-plane anisotropy. The $4\pi M_{\text{eff}}$ for both as-grown and annealed samples is shown in Fig. 5(c). For samples with $t_{\text{CoFeB}} \geq 1.2$ nm, the values of $4\pi M_{\text{eff}}$ for annealed samples are smaller than those without annealing, revealing enhanced interfacial PMA after annealing. For very thin CoFeB layers, the signs of $4\pi M_{\text{eff}}$ change from positive to negative, indicating that the anisotropy field of the system changes from in-plane to out-of-plane.

Fig. 6(a) shows the frequency dependence of the ST-FMR linewidths for the annealed samples. For $t_{\text{CoFeB}} \geq 1.2$ nm, the $\Delta f$ curve still meets a linear relationship. For thinner CoFeB layers ($t_{\text{CoFeB}} = 1.0$ and 1.1 nm), the ST-FMR linewidths of the resonance peaks at $H > H^\text{HFMR}$ exhibit large inhomogeneous broadening, which may be associated with spatial variations in the magnetic anisotropy and interfacial pinning of magnetic moments. The $\Delta f$ for both of the as-grown and the annealed samples with thicker CoFeB layers are plotted as a function of CoFeB thickness in Fig. 6(b). The similar feature demonstrates that the Gilbert damping is almost independent of the annealing effects in thick CoFeB layers.

In conclusion, we investigated the magnetic properties of W/CoFeB/MgO structures by using the ST-FMR...
samples as a function of CoFeB thickness.  

FIG. 6. (a) Linewidth $\Delta$ as a function of resonance frequency $f$ for annealed samples. (b) The Gilbert damping constant $\alpha$ for both as-grown and annealed samples as a function of CoFeB thickness.

technique based on a large SMR effect. The measurements were carried out on both the as-grown and the annealed samples with the different CoFeB layer thicknesses. We extracted the thickness-dependent effective anisotropy fields and damping constants by analyzing the ST-FMR spectra. A non-aligned resonance mode emerges for the annealed samples with thinner CoFeB layers, which have a perpendicular magnetic anisotropy. The observed low-frequency FMR mode has been rarely reported in the previous work, which hints that the ST-FMR technique utilizing SMR may have advantages. For the ST-FMR technique, the resonance signal is measured electrically through detecting the rectified magnetoresistance voltage due to the mixing of the $I_{rf}$ and the $R_{df}$. Therefore, the ST-FMR method is scalable to investigate the small size samples. Furthermore, SMR is more dependent on the spin-dependent scattering at the interface, which makes it less dependent on the film thickness. As a result, the ST-FMR measurement utilizing the SMR effect may have advantages for studying the magnetic properties of ultrathin ferromagnetic films or surface ferromagnetism.

This work was supported in part by C-SPIN and FAME, two of the six centers of STARnet, a Semiconductor Research Corporation program, sponsored by MARCO and DARPA. This work was also supported by the National Science Foundation (ECCS 1611570) and Nanosystems Engineering Research Center for Translational Applications of Nanoscale Multiferroic Systems (TANMS) Cooperative Agreement Award No. EEC-1160504. We would like to acknowledge the collaboration of this research with the King Abdul-Aziz City for Science and Technology (KACST) via The Center of Excellence for Green Nanotechnologies (CEGN). This work acknowledges the support by the Spins and Heat in Nanoscale Electronic Systems (SHINES), an Energy Frontier Research Center funded by the U.S. Department of Energy (DOE), Office of Science, Basic Energy Sciences (BES) under Award No. SC0012670.